

# New Views of the Moon Enabled by Combined Remotely Sensed and Lunar Sample Data Sets, A Lunar Initiative

*Using the hand tool on your Reader, click on the links below to view that particular section of the proposal.*

## Proposal Summary

Scientific/Technical/Management

Objectives and Expected Significance

Background and Impact

Approach and Methodology: The Role of Integration in Fundamental Problems of Lunar Geoscience

Workshop 2: New Views of the Moon II: Understanding the Moon Through the Integration of Diverse Datasets.

Abstract Volume and Subsequent Publications

Statement of Relevance

Work Plan

Potential Workshop (2000): Thermal and Magmatic Evolution of the Moon

Potential Workshop (2001): Early Lunar Differentiation, Core Formation, Effects of Early Planetesimal Impacts, and the Origin of the Moon's Global Asymmetry

Potential Workshop (2002): Selection of Sites for Future Sample Return

Capstone Publication

Timeline for the New Views of the Moon Initiative

Personnel: Initiative Management and Proposal Management

References

Facilities: The LPI

Appendix 1. Workshop on New Views of the Moon: Integrated Remotely Sensed, Geophysical, and Sample Datasets. List of presentations

Appendix 2. LPSC 30 (1999) special sessions related to the Lunar Initiative.

List of presentations (oral and poster)

Appendix 3. Lunar Initiative Steering Committee

Web Note: This is the text of a proposal submitted on behalf of the Lunar Science Community to support ongoing workshops and activities associated with the CAPTEM Lunar Initiative. It was submitted in May, 1999, in response to the ROSS 99 NRA, which solicits such proposals to be submitted to the relevant research programs. This proposal was submitted jointly to *Cosmochemistry* and *Planetary Geology and Geophysics*.

## *Proposal Title*

### New Views of the Moon Enabled by Combined Remotely Sensed and Lunar Sample Data Sets, A Lunar Initiative

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## PROPOSAL SUMMARY

### **TITLE: New Views of the Moon Enabled by Combined Remotely Sensed and Lunar Sample Data Sets, A Lunar Initiative**

A Proposal Submitted to Cosmochemistry and Planetary Geology and Geophysics on behalf of CAPTEM (Curation Analysis and Planning Team for Extraterrestrial Materials) and the Lunar Science Community

INSTITUTION: Lunar and Planetary Institute

### **ABSTRACT**

1) This is a proposal to Cosmochemistry and Planetary Geology and Geophysics on behalf of the lunar science community and as part of the CAPTEM-led initiative, *New Views of the Moon Enabled by Combined Remotely Sensed and Lunar Sample Data Sets*. This initiative involves the participation of the remote-sensing, geophysical, and sample-analysis communities. Global data sets obtained by the Clementine and Lunar Prospector missions are providing new information that, when coupled with extant sample, experimental, geophysical, and remotely sensed data, is leading to significantly improved understanding of the origin and geologic evolution of the Moon and its present-day distribution of resources. Global geochemical data sets are being used to redefine major crustal provinces. Vastly improved resolution of the gravity field is allowing increasingly sophisticated models of crust and mantle structure, and high resolution of the remanent magnetic field suggests the existence of a small core. Data from the Lunar Prospector neutron spectrometer is providing characterization of the nature and extent of hydrogen concentrations at the lunar poles. It is imperative that these data sets be synthesized and integrated with one another and with the lunar-sample data set, which provides ground truth for many of the remote observations. The purpose of this initiative is to organize activities and to foster collaborations that bring together diverse scientific communities and to develop integrated approaches to understanding the Moon. Activities associated with this initiative include LPI-facilitated workshops and advocacy of topical sessions at national meetings. Funds are requested for administrative costs associated with workshops, student travel to workshops, partial support for travel for convenors and invited speakers of workshops, and publication of a volume summarizing important advances in lunar science and integration of new concepts associated with emerging global data sets. Our capstone product at the end of this initiative will be a written volume organized according to a team concept for integration and handling of specific topical areas. Partial support for that publication (page charges) is requested in the third year. 2) This is a renewal proposal; \$25K was provided by Cosmochemistry in FY99 for workshop expenses. 3) A workshop was held at the LPI in September, 1998, entitled "New Views of the Moon: Integrated Remotely Sensed, Geophysical, and Sample Datasets." About 90 individuals participated in the workshop and 51 abstracts were presented and discussed. Topical sessions were organized for both the 29th and the 30th Lunar and Planetary Science Conferences. At LPSC 30, the number of abstracts submitted warranted two special sessions, *New Moon I: Hot Spots, Gravity, And Magnetism* and *New Moon II: Major Lunar Terrains*. Strong attendance and discussion reflected a renewed enthusiasm for lunar studies. The need to extract the maximum information content from these diverse data sets and to critically examine the Moon's origin and geologic history, and its distribution of resources in the light of the new and recently obtained data sets is evident. A second LPI workshop is scheduled for Sept. 22–24, 1999, in Flagstaff, Arizona. The workshop will focus on seven specific topical areas that will benefit most from the application of integrated scientific approaches. We will also use this workshop to begin organizing for the production of the capstone publication. 4) Relevant Publications (see also appendix 1 and 2)

Jolliff B. L. and Ryder G., eds. (1998) Workshop on New Views of the Moon: Integrated Remotely Sensed, Geophysical, and Sample Datasets. LPI Contribution No. 958, Lunar and Planetary Institute, Houston. 87 pp.

Appendix 1: List of abstracts from the Moon98 Workshop, September, 1998

Appendix 2: List of abstracts from the special sessions at the 30th LPSC, March 1999

## **NEW VIEWS OF THE MOON ENABLED BY COMBINED REMOTELY SENSED AND LUNAR SAMPLE DATA SETS, A LUNAR INITIATIVE II**

### **Scientific/Technical/Management**

#### **Objectives and Expected Significance**

As results of the Lunar Prospector mission continue to become available, and with the results of the Galileo and Clementine missions now providing new global data of the Moon, it is imperative that we synthesize these new data and integrate them with one another and with the lunar-sample database. Toward this end, CAPTEM (Curation and Analysis Planning Team for Extraterrestrial Materials) has organized a scientific initiative entitled “*New Views of the Moon Enabled by Combined Remotely Sensed and Lunar Sample Data Sets.*” The purpose of the initiative is to foster interdisciplinary science to tackle questions regarding the origin and evolution of the Moon and to pursue in the most efficient manner possible the new ideas that are emerging from the recently obtained global data. We also seek to optimize the utility of existing data through this integrative approach. One logical outcome of this effort will be to place the lunar science and exploration community in a much better position to carry out focused future missions to the Moon. Our main approach to conducting this initiative is through a series of focused workshops and special sessions at national meetings to promote interest, interaction, and continuity of effort, culminating in a capstone publication that will show how these important data sets, including the Apollo-acquired samples and lunar meteorites, can be used together to understand the Moon.

The purpose of this CAPTEM initiative is to facilitate interactions and intellectual cooperation between the lunar remote-sensing, geophysical, and sample communities, which will potentially lead to fundamentally new views of the Moon’s internal structure, surface geology, magmatism and volcanism, and crustal and regolith evolution through time. ***The purpose of this proposal is to help accomplish these goals through a series of workshops (one per year) focused specifically on the issue of integration of data sets and on multidisciplinary approaches.*** We have concluded that a summary publication is required (including CD formats); this will both summarize the major lunar data sets and detail how they can be integrated to provide the best possible unified statement of the geologic history of the Moon at the present time. This proposal requests support for that publication in the third year.

#### **Background and Impact**

It has been over 25 years since Apollo 17 returned the last of the Apollo lunar samples. In the time since then, a vast amount of data has been obtained from the study of rocks and soils from the Apollo and Luna sample collections and, more recently, on a set of about a dozen lunar meteorites collected on Earth. Based on direct studies of the samples, many constraints have been established for the age, early differentiation, crust and mantle structure, and subsequent impact modification of the Moon. In addition, geophysical experiments at the surface, and remote sensing from orbit and Earth-based telescopic studies have provided additional data sets about the Moon that constrain the nature of its surface and internal structure.

In 1990 and 1992, the Galileo spacecraft encountered the Earth-Moon system and provided multispectral views of the Moon new perspective, which added significantly to the body of knowledge gained from Apollo-era studies and Earth-based telescopic studies (e.g., Pieters et al., 1993). Then, in 1994, the joint DOD-NASA Clementine mission provided the first global or near-global data sets for lunar gravity, topography, and multispectral imaging. Scientific results from the Clementine data exceeded expectations (first-order results summarized by McEwen and Robinson, 1997), and refinements to those data continue to provide a useful base for further investigations (Eliason et al., 1998, 1999; Robinson et al., 1999). Results to date from the Lunar Prospector mission are nothing less than spectacular (Binder et al., 1998; Feldman et al., 1998; Konopliv, 1998; Lawrence et al., 1998; Maurice et al., 1998; Munoz et al., 1998; and many LPSC XXX abstracts). Examples of some of these results are provided below and in many of the abstracts listed in the Appendices.

Despite the apparent wealth of data, we do not know all there is to know about the Moon, which some may consider to be a relatively simple geologic body. To the contrary, the ongoing *Lunar Prospector* mission and the highly successful *Clementine* mission, as well as recent sample-based geochemical, isotopic, experimental, and theoretical studies, have provided important clues to the real geological complexity of the Moon, and have shown us that we still do not yet adequately understand the early geologic history of Earth's companion. The *Clementine* and *Lunar Prospector* missions, like *Galileo* during its lunar flyby, are providing global information viewed through new kinds of windows – and providing a fresh context for models of lunar origin, evolution, and resources, and are providing the impetus for *new questions and new hypotheses*. The probable detection and characterization of water-ice at the poles, the extreme concentration of Th and other radioactive elements in the Procellarum-Imbrium-Frigoris resurfaced areas of the nearside of the Moon, and the high-resolution gravity modeling enabled by these missions are examples of the kinds of exciting new results that must be integrated with the extant body of knowledge based on sample studies, in-situ experiments, and remote-sensing missions to bring about the best possible understanding of the Moon, its history, and its resources.

Numerous research groups have already begun to capitalize on the Clementine data sets and to integrate the new data with results from studies of rocks and soils collected during the Apollo missions, from studies of the geology of the landing sites (e.g., Blewett et al., 1997; Lucey et al., 1998a, c, d), and from studies of the results of Apollo geophysical experiments (e.g., Neumann et al., 1996, 1998; Wieczorek and Phillips, 1998, 1999; Konopliv et al., 1999; Hood et al., 1999b). Even those research groups that, to this point, have focused primarily on the lunar samples are beginning to recognize the importance and utility of the remotely-sensed data sets and the need to couple our understanding of the lunar samples with the wealth of information contained in the new data sets. Extending our understanding of lunar geology and resources from the landing-site scale to a truly global scale will provide the foundation for new paradigms of the Moon's geologic evolution as well as a foundation for studies that pave the way to future resource utilization, on-surface experiments, and manned lunar-outpost missions.

A number of recent and ongoing efforts focus on the remotely-sensed data in terms of lunar soil characteristics. These include laboratory spectroscopic studies (e.g., Fischer and Pieters, 1994; Pieters, 1998), highly accurate electron petrography of finest fractions of lunar soil (Taylor et al., 1997, 1998a, b, 1999), high-resolution TEM investigations of irradiated rims coating soil particles and surface vapor deposits (Keller et al., 1998, 1999), and theoretical work on the effects of submicroscopic Fe metal on the absorption and reflectance properties of lunar soil (Hapke, 1998). These studies appear to be converging toward a quantitative solution to understanding the causes and optical effects of lunar soil maturity. Other efforts have focused on calibration of remotely sensed data with the characteristics of soils and geology of the lunar landing sites (e.g., Blewett et al., 1997; Lucey et al., 1998a; Gillis et al., 1999; Lawrence et al., 1999). Work of this kind is crucial to furthering our ability to extract the full measure of information from the new data sets.

The first activity related to the initiative occurred at the 29th Lunar and Planetary Science Conference in the form of a special topical session entitled “*Probing the Moon with Remote Sensing and Samples: A New Integration.*” We held our first workshop Sept. 18–20, 1998, at the Lunar and Planetary Institute in Houston. At the 30<sup>th</sup> LPSC, we organized two special sessions, Moon I and Moon II, and a related poster session. A second workshop has been planned for Sept. 22–24, 1999, to be held in Flagstaff, Arizona. The subsequent workshops are the objective of this proposal.

The long-term or “capstone” goal of the initiative is to produce a volume that summarizes the state of our understanding of the Moon based upon the new global data sets, integrated with what we learned from Apollo samples and related studies and other remotely sensed data sets. We envision the scope of this publication as being similar to that of *Basaltic Volcanism on the Terrestrial Planets* (in usefulness and quality, though not in vastness) and we see this coming together in the final year of the initiative. We plan to assemble a CD-ROM that would correspond to the volume, which would contain images, selected data sets or portions thereof, and some examples of derived products. The concept of this volume, the related CD-ROM, and the workshops all have the common objective of bringing together diverse disciplines of lunar science to gain a mutual understanding of the different data sets, to identify common, fundamental problems that we seek to solve, and to foster the multidisciplinary interactions that will provide the maximum scientific return from the available data sets.

**Steering Committee.** We have in place a steering committee, consisting of individuals with expertise including lunar geology, remote sensing, geophysics, mineralogy, petrology, and geochemistry; and representing the breadth of current and coming data sets. The members of the steering committee are listed in Appendix 3. The first topical session at the 29th LPSC and the first workshop announcements are being used to communicate the initiative to the broader community. In addition, we have placed an article in the *Lunar News* (February, 1998) and we are setting up an Internet web site through the Lunar and Planetary Institute.

**Why this emphasis now?** *The timing is right for this initiative.* Data sets obtained by the 1994 Clementine mission are approaching a state of maturity in the following sense. Gravity data derived from the Clementine mission have fueled a new set of studies and interpretations regarding the internal structure of the Moon (e.g., Zuber et al., 1994; Neumann et al., 1996; Wieczorek and Phillips, 1998; Konopliv et al., 1998). Established and tested calibration procedures, developed over the past three years, are available and in use for the UV-VIS data (Brown University group ([www.planetary.brown.edu/clementine/index.html](http://www.planetary.brown.edu/clementine/index.html)), U.S. Geological Survey ([www.flag.wr.usgs.gov/isis-bin//clementine\\_mosaic.cgi](http://www.flag.wr.usgs.gov/isis-bin//clementine_mosaic.cgi))). The Clementine UV-VIS data are providing the means to do local and regional studies of lunar surface materials almost anywhere on the Moon, as well as global studies of surface composition. Calibration procedures for the Clementine NIR data are anticipated soon (Lucey et al., 1997a, b, 1998e) and will extend the multispectral range available for mineralogical and compositional studies. Lunar Prospector neutron and gamma-ray data are now being obtained (Binder et al., 1998; Feldman et al., 1998; Lawrence et al., 1998) and soon will provide a synergistic cross correlation with the Clementine data for information that can be determined using data from both missions, such as FeO concentration of surface soils (Munoz et al., 1998). The high spatial resolution of the Clementine multispectral data and the extended set of major-element compositions determined from the Prospector gamma-ray data will each serve to enhance the value of the other data set. Such cross-correlated data will enable direct tests of specific hypotheses regarding the global distribution of elements that are important to interpretations of lunar crustal genesis and present-day distribution of materials. For example, using Clementine data, Lucey et al. (1995, 1998a) have developed procedures for estimating Fe and Ti concentrations; these will also be determined globally from the Lunar Prospector

gamma-ray data, and both data sets can be cross correlated to data taken directly on soils at the Apollo and Luna landing sites. Because the spatial resolution of the gamma-ray experiment will be low (~50 km, Feldman et al., 1996), Clementine data will be crucial to provide a link enabling this three-way cross correlation.

The Moon is the keystone to our understanding of the silicate bodies of the solar system.. The Moon is the only other object for which we have samples of known spatial context. Studies of the Moon and the lunar samples established the concept of primary differentiation of planetary crusts, the relative time scale based on cratering statistics, and a record of early solar system exogenic processes (LGO, 1986). Understanding the Moon's origin is key to understanding the Earth's early history, and the Moon, because of its relatively simple silicate differentiation and lack of surface chemical weathering, serves as a baseline to study more complex planetary processes. NASA is now actively involved in programs to study other solar system objects using remote sensing and, eventually, sample returns. With the Moon, we have the opportunity *and the obligation* not only to understand its origin and history, but to determine the best ways to integrate diverse types of data for the maximum scientific return. What kinds of samples and sampling strategies will be the most useful for interpretation of remotely sensed data? What laboratory measurements can be made to further our understanding of the remotely sensed data? What are the common questions that the different disciplines seek to answer and how can we best work together toward that end?

**What the Initiative is not.** First, this initiative is not an attempt to produce archives of any specific mission data sets. We fully recognize the functions of specific mission PI teams for planetary data-set development and the different nodes of the NASA Planetary Data System for data-set production, access, usage, and archival. We seek instead to better understand the major data sets across disciplines and to provide information and ideas about how to engage those data sets toward the solution of common problems. Second, the initiative is not an attempt to promote research aimed at developing a specific data set. However, a recognition of important gaps in key data sets may be an outcome of early activities of the initiative. It is hoped that research groups having the capability to fill such gaps will endeavor to do so.

### **Approach and Methodology: The Role of Integration in Fundamental Problems of Lunar Geoscience**

The 1986 Report *Contributions of a Lunar Geoscience Observer (LGO) Mission to Fundamental Questions in Lunar Science* laid out in detail many of the important questions remaining in lunar geoscience that could be addressed by a mission involving global multispectral imaging, X-ray and gamma-ray mapping, radar altimetry and Doppler tracking, and magnetometer and electron reflectometer experiments. These questions remain just as relevant today as they were then; however, many of the data sets envisioned at that time have been or are in the process of being obtained in some form. The fundamental problems as listed in the LGO report will not be repeated here, but to provide an idea of the scope envisioned for the present initiative, we summarize below some of the fundamental questions for which multidisciplinary approaches can potentially make significant advances.

#### **1) What is the vertical and lateral structure of the lunar crust and how did the crust evolve?**

Geophysical crustal thickness models based on seismic, gravity, and topography data currently assume a single or dual layered crust (e.g., Wieczorek and Phillips, 1998). Multispectral studies of central peaks of craters (e.g., Tompkins and Pieters, 1998) and basin uplift structures may be able to constrain or improve upon these simple models. By carefully modeling of the composition of ejecta deposits from basins, it



will be possible to infer the structure beneath the largest basins. Apollo samples provide real constraints for the geophysical models.

## **2) What is the composition and structure of the lunar mantle?**

Seismic velocity models provide geophysical constraints on lunar mantle structure and for changes in mineralogical phases and density. Constraints on composition are provided by petrologic studies of lunar basalts and pyroclastic materials thought to have erupted from different depths within the upper mantle (e.g., BVSP, 1981; Neal, 1998). Other constraints are derived from consideration of bulk lunar composition and structure (now better defined using remotely sensed data) and the proportion of the Moon that must have undergone differentiation to produce the observed crust. Thus, improved models of crustal structure will contribute to better models for the mantle. Limits on the size of a metallic core from electromagnetic sounding will also help in the evaluation of mantle density models through moment-of-inertia and mean density constraints (LGO, 1986).

## **3) What was the extent of a lunar magma ocean?**

The concept of the lunar magma ocean depends almost entirely on our understanding of the composition and structure of the Moon's crust. One of the keys to that understanding is knowing the distribution of plagioclase, corresponding (cogenetic) mafic minerals, and incompatible elements (KREEP). Another key is knowing the extent of variability and whether those materials are related to global differentiation layers or bodies, serial or isolated intrusive rocks, or differentiates of thick, basin impact melt. Where do large bodies of anorthosite crop out on the Moon (e.g., Hawke et al., 1992) and how large must the system have been that produced them? Global, high-resolution multispectral data coupled with global gamma-ray data will constrain how these materials vary laterally and vertically in the crust. The Apollo samples are the key to these interpretations because they provide firsthand knowledge of rock types, lithologic associations, detailed chemical compositions, age dates, and depth constraints.

## **4) How is the surface expression of lunar materials related to the Moon's internal structure and evolution? (or Where exactly do the different rock types come from?)**

The major lunar highland rock types are known from the Apollo samples. Little is known, however, about the exact place of origin of the igneous rocks because none were sampled in place. Uplift structures associated with large impact craters and basins may expose crustal igneous rocks, and mineralogical remote sensing of these structures can provide important clues to the lateral distribution of different types of igneous rocks and their pre-impact depths of formation (e.g., Tompkins and Pieters, 1998). The composition of regions of megaregolith, determined by remote geochemical analysis, can provide information about the types of rocks exhumed from basin impacts, especially for those formations that can be associated with a specific basin of origin (e.g., Haskin, 1998). From these clues, it should be possible to back out the distribution and abundance of important rock types such as anorthosite (assuming large bodies of anorthosite to be of the ferroan variety and original products of a magma ocean), and the magnesian suite of plutonic rocks including norite, troctolite, and gabbro. Geophysical models provide critical tests of whether the vertical and lateral distributions of rock types inferred from surface data are consistent with gravity and topography data.

## **5) What is the nature of the Moon's asymmetry, what caused it, and what are the implications for the Moon's internal evolution and present-day distribution of materials?**

What is the nature of the lunar center-of-mass/center-of figure offset? Geophysical models suggest either an increase in crustal density for the lunar nearside, or a thickened farside crust (Neumann et al., 1996;

Wieczorek and Phillips, 1998). From remote compositional analysis of the regolith, it may be possible to infer/confirm lateral density variations, and the presence or absence of ejected mantle material from large basins may help constrain the thickness of the crust far from the Apollo seismic stations. Knowledge of the distribution of surface materials using multispectral and geochemical analysis on a global scale may show a global compositional asymmetry as well. If that can be shown to predate the formation of the major nearside basins, then it may be shown that the early lunar crustal differentiation was heterogeneous on a global scale with important consequences such as the concentration of KREEP residua under the Procellarum region, as suggested by Haskin (1998). If such asymmetry existed early in the Moon's history, subsequent thermal evolution may have been driven in large part by the non-uniform concentration of radioactive elements. Key to answering this question is translating from the Apollo samples of known composition and rock type to the successful identification of rock types and compositions by remote techniques.

#### **6) What is the origin, evolution, and distribution of mare volcanism?**

Mare basalts, although volumetrically minor, formed by partial melting of the lunar mantle and thus record compositions, mineralogy, and processes from as deep as 200 to 400 km. Basalts sampled by the Apollo and Luna missions range in age from 3.9 to 3.1 Ga; however, significantly younger volcanism is indicated by crater densities and volcanism as old as 4.2 Ga is recorded by basalt clasts in impact breccias. The sampled basalts and related pyroclastic glasses cover a broad range in composition, for example from <1 to 16 wt.% TiO<sub>2</sub>. However, spectroscopic data suggest that perhaps less than half of the mare basalt types on the Moon have been sampled and little is known about the farside maria. Systematic relationships between mare basalt age and chemistry are proving to be more elusive than thought in early studies of Apollo basalts. Volatile-rich pyroclastic eruptions were an important part of lunar mare volcanism; these deposits need to be mapped, dated, and understood in terms of eruptive volume and duration.

#### **7) What were the timing and effects of the major basin-forming impacts on lunar crustal stratigraphy? What is the nature of the South-Pole Aitken Basin and how did it affect early lunar crustal evolution?**

Impact is perhaps the most important process in the assembly and early history of the terrestrial planets, and basin impacts are the most important events in shaping the large-scale features of the Moon's present day surface. Because of its simple tectonic style, or lack thereof, the Moon preserves a relatively complete record of its early bombardment. Much work remains to be done to sort out the detailed stratigraphy of the lunar basin deposits. In the absence of direct, in-place samples of impact-melt sheets for geochronology, it will be the task of mineralogical and geochemical remote sensing coupled with photogeology to improve our knowledge of the timing and the effects of basin formation. Integrating the timing of basin impacts with the likely thermal evolution of the Moon may provide explanations for the nature of the geophysical (mascon) anomalies, for example, where large basins such as Imbrium and South-Pole Aitken appear not to have excavated as deeply as might be expected based on their diameter (Wieczorek and Phillips, 1998). The implications of the enormous South-Pole Aitken basin for early lunar evolution are currently a hot topic (Pieters et al., 1997; Yingst and Head, 1997; Lucey et al., 1998b; Warren, 1998) and will continue to be a target of intensive study.

#### **8) What are the origins of lunar paleomagnetism?**

The magnetization of surface materials, if related to a core dynamo, imply the presence of a metallic and core and thus have great significance for the early differentiation and thermal evolution of the Moon.

Strong localized magnetic anomalies have been detected from orbit, but their origins have not been determined. A variety of mechanisms have been proposed, and the currently favored hypothesis relates to magnetization of regions antipodal to major impact basins (e.g., Lin et al., 1988; Hood and Williams, 1989). Experiments involving the magnetometer and electron reflectometer (Lunar Prospector) will provide a global map of magnetic anomalies, and correlation to global mineralogical and geochemical data sets, coupled with known magnetization properties of the Apollo samples, may go a long way toward resolving the causes of lunar paleomagnetism.

**9) What are the Moon's important resources, where are they concentrated, and how can they be harvested?**

The Moon will figure prominently in future space exploration as a place where human beings will learn how to survive on the hostile surface of another planet. The Moon has abundant resources of oxygen, hydrogen, and other solar-wind gases trapped in its regolith. And, based on the results of the Clementine bi-static radar experiment and the recent Lunar Prospector neutron spectrometer, there may be significant quantities of water ice in the regolith in permanently shadowed craters at both poles. Some soils have high concentrations of iron and titanium, which could be recovered during the processing of regolith for its gases. Understanding the siting of such resources, from the perspectives of mineralogy, lithology, and regional and specific geology, is prerequisite to efficient human presence on the Moon.

In addition to (and in many cases, prerequisite to) addressing the fundamental science questions, we will address issues related to usage and constraints of the remote-sensing, geophysical, and sample data sets. Underlying each of the questions above is the need to calibrate and interpret correctly the remote data. This task is made difficult by the effects of space weathering and the near ubiquitous regolith whose composition is made uniform by impact mixing of surface materials. The advantage of the Moon is that rock samples exist for known landing sites, and the composition of the regolith at those sites is also known. Thus, there exists a natural means for calibrating the remotely sensed data.

**Workshop 2. New Views of the Moon II: Understanding the Moon Through the Integration of Diverse Datasets. September 22–24, 1999, Flagstaff, Arizona**

**Organizing Committee**

Lisa Gaddis: U.S. Geological Survey.  
Brad Jolliff: Washington University  
David Lawrence: Los Alamos National Laboratory  
Paul Lucey: University of Hawaii  
Clive Neal: University of Notre Dame  
Greg Neumann: Massachusetts Institute of Technology  
Graham Ryder: Lunar and Planetary Institute  
Charles Shearer: University of New Mexico

**Purpose and Scope**

Building upon the success of the first Lunar Initiative workshop, the purposes of the second workshop are to foster a community-wide effort to synthesize and interpret remotely sensed data in terms of known surface materials on the Moon, and to facilitate use of diverse data sets in an integrated way to address problems of the origin, planetary evolution, and resources of Earth's nearest neighbor. New techniques for integrated analyses of multiple datasets are currently under development, and being used to address several major themes in lunar science, including: lunar differentiation, crustal evolution, basaltic

volcanism, global resources, lunar surface characterization, integrated approaches to studies of the lunar surface and interior, and status of Clementine and Lunar Prospector global data.

The workshop will be held at the Museum of Northern Arizona, in Flagstaff, Arizona, on September 22, 23, and 24. It will include overview and contributed presentations, with ample time for discussion focusing on topics and issues of common interest. A poster session, with a possible computer demonstration, may be held during one of the evenings. There will be structured time for breakout groups to form and discuss plans for the Initiative-related capstone publication outlined above.

Session topics will include:

- 1) Current state and fine-tuning of major global and sample data sets, and projection of future needs
- 2) Lunar origin, lunar differentiation, and the origin of global asymmetry
- 3) Thermal evolution and magmatism subsequent to initial differentiation
- 4) Impact history of the moon: role of large basin impacts
- 5) Lunar structure, core, and magnetism
- 6) Lunar regolith composition and evolution from orbit to TEM scales
- 7) Lunar resources

### **Abstract Volume and Subsequent Publications**

The workshop will have an abstract volume (electronic abstract deadline July 2, 1999). A special issue of JGR-Planets is planned to include papers deriving from the workshop. One focus of this workshop will be to organize the preparation of a major publication summarizing state-of-the-art knowledge of the lunar remote sensing and sample data collection, including characterization of the inherent advantages and limitations of each data set, and recommendations on how and to what end specific data are best used. As part of this process, we will discuss our group role in advocating, gathering, processing, archiving, and distributing lunar data---including sample data and reference suites---for current and future science efforts. The ultimate goal of this publication is to provide (1) a summary of what data are available, (2) an explanation of how the data have been and might continue to be used to develop integrated theories for the geologic evolution of the Moon, and (3) recommendations for data to be acquired and future research directions.

### **Statement of Relevance**

The acquisition of global lunar data sets by the recent Clementine and Lunar Prospector missions are providing the potential opportunity to advance our knowledge of the Moon's surface characteristics, geophysics, geologic history, and resource distribution in a manner unprecedented since the time of the Apollo missions. The Moon is Earth's nearest neighbor; its surface holds clues to the past impact history of the Earth-Moon system, including the likely formation of the Moon as a result of an early giant impact on Earth. The Moon is a logical and crucial stepping stone in NASA's systematic exploration of the Solar System and it holds important resources for use in that exploration. It is incumbent upon us to exploit to the fullest the new global data sets, coupled with Apollo sample science and site geology, to better understand Earth's partner in the Solar System.

### **Work Plan**

We propose to hold one workshop each year during the next three years, beyond the one described above. Specific plans and topics for each workshop will be developed each year at the conclusion of the preceding workshop by the participants so as to keep focused on topics of the most active and productive research. More topics are evident than time to hold workshops on them. However, based upon results of

the past workshop and recent special sessions, we propose the following workshop titles and descriptions as a working list.

### **Potential Workshop (2000): Thermal and Magmatic Evolution of the Moon**

Newly acquired data sets coupled with several current lines of research indicate that models for the thermal and magmatic evolution of the Moon can be advanced significantly. First and foremost is the great concentration of Th and related heat producing elements (Lawrence et al., 1998, 1999) in the Procellarum-Imbrium region shown clearly in gamma-ray spectrometer data from Lunar Prospector. Implications for secondary magma generation are enormous both for the crust (Wieczorek and Phillips, 1999; Korotev, 1999) as well as for the mantle (Parmentier and Hess, 1999). Measurements of the Moon's induced magnetic dipole moment have been used to suggest the existence and size of a metallic Fe core (Hood et al., 1999). The formation of an iron core of 375 km radius would also have implications for the thermal evolution of the Moon. Petrologic and geochemical modelling based on recent experimental results and analyses, including isotopic studies, are providing new constraints on the depth of melting and the nature of source regions of mare basalts and picritic glasses (Neal, 1998; Snyder and Taylor, 1998; Longhi, 1992; Neal et al., 1999). Even so, the depth of the cumulate mantle produced by magma-ocean crystallization and the possible existence of a primitive lower mantle have not been resolved. Remote sensing provides information about relative ages, timing of eruptive phases, eruption volumes, and compositions of erupted units (Head, 1998). Such information, coupled with geochronologic constraints, provides a framework for understanding the internal evolution of the mantle source regions. We believe these topics are ripe for a workshop and we will pursue this theme for a workshop in 2000.

### **Potential Workshop (2001): Early Lunar Differentiation, Core Formation, Effects of Early Planetesimal Impacts, and the Origin of the Moon's Global Asymmetry.**

The lunar magma-ocean model remains as a strong conceptual framework for the early, extensive differentiation of the Moon (Warren, 1998). It is unclear, however, just how the crystallization of the magma ocean proceeded, and whether it produced one of the largest layered igneous bodies in the Solar System (i.e., a Stillwater-like crust) or whether it produced a series of stacked massif-anorthosite bodies similar to the giant terrestrial massif anorthosites of Proterozoic age (e.g., Longhi et al., 1999). If the Moon has a core, what is it made of, when did it form, and how did it affect magma-ocean formation/crystallization? New global data as well as previous sample, geophysical, and remote-sensing studies have shown that lunar global asymmetry is manifest in many ways, including surface geochemistry, volcanic resurfacing, crustal thickness, and rock chemistry. At present, there is a lack of understanding of how the asymmetry was obtained. Warren and Kallemeyn (1998) suggested that a giant Procellarum basin impact into a partially solidified magma ocean may have been the driving force to concentrate urKREEP residual melt in the Procellarum region. However, geophysical evidence for a Procellarum basin and geochronologic evidence for ancient impact melts of appropriate composition and age are lacking. Others suggestions include some sort of tidal pumping force to concentrate residual melt within the nearside crust, and filling in of basin impacts into the Procellarum-Imbrium region where a molten or near-molten concentration or layer of urKREEP or KREEP-basalt-like melt resided (Haskin, 1998; Wieczorek and Phillips, 1999). These topics constitute a major gap in our understanding of the evolution of the Moon; deciphering the record for the Moon may help us also to understand the evolution of other large satellites within the Solar System.

## Potential Workshop (2002): Selection of Sites for Future Sample Return

With the expectation of a return mission or missions to the Moon within the next decade, it is timely now to use all available data sources to select and characterize those sites having the most potential for resource exploitation or advancing our scientific understanding of a lunar geologic process or region. The tantalizing suggestion of large quantities of water ice in soils within permanently shadowed polar regions (Nozette et al., 1996; Feldman, 1998) begs a surface mission for confirmation and characterization of the deposits. Remote sensing suggests that numerous regions of the lunar surface comprise rocks of types that have not yet been sampled, such as the floor of South Pole-Aitken basin, or regions of volcanic domes possibly formed by higher viscosity lavas than typical mare basalts. Samples of the youngest basalt flows, made available for geochronologic study, would provide a strong constraint on thermal dissipation in the mantle and would provide an important calibration point for relative ages based on crater densities. We envision a workshop that would invite focused views and integrated research on the most promising sites where samples or in-situ information have the greatest potential for improving our understanding of the Moon. The product of such a workshop would be a cornerstone document listing the most important sites for return missions to the Moon, and detailing their justification. We believe that such a workshop would be a fitting end-product of the workshop phase of the initiative and would provide a very practical and useful function.

## Capstone Publication

During the initiative, many research results will produce papers that will be published in the normal scientific journals, e.g., a special issue of JGR-Planets for the second workshop, and funded through normal research channels. However, toward the end of the Initiative, which is expected to be within the next three years, we intend to produce a “capstone” publication, patterned after the volume *Basaltic Volcanism on the Terrestrial Planets*. In the capstone volume, we have the following broad objectives: (1) to summarize the lunar data sets, (2) to apply multidisciplinary approaches using the applicable data sets to fundamental problems, and (3) to address the utilization of lunar resources, siting of lunar bases, and future desired data sets. This is not intended to be the end-all publication; instead, it will be a strong statement of where we stand at the beginning of the 21st century with regard to some of the key questions of lunar geoscience. Nonetheless, unless further missions are planned, it should be a very powerful summary of the state of knowledge possible using existing data sets. It should help to focus future research efforts and it should stand as an example of how to use diverse global data sets in an integrated way to address fundamental problems of planetary science. We propose that this capstone publication be funded by page charges administered coherently through the LPI.

Proposed Topics for Initiative Volume [Book (BVSP format) + CD-ROM (PDS-produced)]. These topics and organization will be continuously discussed, scrutinized, and revised; however, they are listed here to provide an idea of what we have in mind.

### Introduction

- Aim
- Mineralogy, petrology, and geochemistry for lunar geoscientists
- Remote sensing for lunar geoscientists
- Geophysics for lunar geoscientists
- Geology of the Lunar landing sites

### Lunar Samples

identify reference suites data or subset on CD-ROM

- Lunar rocks
- Lunar soils and cores
- Lunar meteorites

### Remote Sensing & Geophysical Data Sets

- Earth-based telescopic data
  - Lunar Orbiter imagery & Surveyor/Apollo orbital photography
  - Apollo surface geophysics
  - Apollo X-ray and gamma-ray
  - Geophysical data (gravity, magnetic, radar)
  - Galileo
  - Clementine (subdivided) - Prospector (subdivided)
  - mission/experiment summary
  - summary of data acquisition
  - processing (calibration, photometry, etc.)
  - archival and access
  - usage: strengths, limitations
  - reference samples, spectra, images, cross-references to other sources
  - extensive bibliography
- (example or key data on CD-ROM)

### Laboratory studies, calibration efforts, processing integrated data sets

- Basic characteristics of surface materials: petrography - mineralogy, maturity, grain size studies and effects on remotely sensed data sets
- Reflectance spectroscopy (and others)
- tie specific sample characteristics to remotely sensed data
- How to extract mineralogy, petrology, & geochemistry from remotely sensed data - integrating multiple data sets
- Apollo - Luna landing site studies & correlations
- Lunar GIS (Geographic Information Systems) development

### Applications (key workshop consensus and results to date; more like *BVSP* than *Sourcebook*)

\*Synthesis & integration of results thus far from multidisciplinary approaches using diverse data sets (summary style, with statements of how next to proceed; extensive reference lists).

Potential topics:

- Origin of the Moon
- lunar structure and early differentiation
- lunar bulk composition
- existence of core
- Evolution of lunar crust and mantle
- magma ocean concept
- crustal thickness and structure
- depth of early lunar differentiation
- structure and composition of the mantle
- Magmatic history
- intrusive igneous activity
- mare volcanism

- History and nature of impact processes
- bombardment effects
- crater and basin crustal modification and ejecta distribution
- Thermal history
- effects of major differentiation effects (endogenic & exogenic)
- modes of heat transfer
- Origin of lunar paleomagnetism
- pervasive
- localized
- Nature of the lunar regolith
- soil-forming processes
- regolith relation to local/regional rock units and geology

\*What do we know, now that we have these data sets?

How has this changed the way we approach local and regional geologic problems?

How has this changed our thinking about the origin, evolution, and structure of the Moon?

#### Forward Look - Recommendations

- Lunar resources and lunar-base site definition & studies
- Summary of results of last workshop on recommendations for in-situ investigations and sample-return site selection
- Future desired data sets (for example):
  - global topography - (e.g., orbital radar at high resolution)
  - spectra on reference soils and rocks
  - high resolution (spatial and energy) gamma-ray
  - active seismic arrays
  - using remote sensing to identify key areas for remote sample returns
  - what future missions/areas/samples/data sets are high priority?

#### **Timeline for the New Views of the Moon Initiative**

Sept. 18–20, 1998	LPI workshop, Houston, Texas - Completed
Sept. 22–24, 1999	Second Workshop, Flagstaff, Arizona – On schedule - present Initiative capstone volume concepts
2000	Third Workshop - develop team organization - develop concepts for CD-ROM
2001	Fourth Workshop - first draft, Initiative capstone volume
2002	Fifth Workshop - final draft of Initiative capstone volume

#### **Personnel: Initiative Management and Proposal Management**

This Proposal is a *part* of the New Views of the Moon Initiative, although a significant part. The Initiative was begun and organized by CAPTEM (Curation Analysis Planning Team for Extraterrestrial



Materials) under the Chairmanship of J. J. Papike. CAPTEM reports to the Discipline Scientist for Cosmochemistry. G. Ryder and B. L. Jolliff are co-chairs for the Initiative on behalf of CAPTEM, and J. J. Papike and C. R. Neal are also CAPTEM subcommittee members for the lunar initiative. Paul Lucey brings expertise in the fields of remote-sensing and spectroscopy. A steering committee has been formed consisting of twenty-one individuals from the lunar science community and representing a diversity of disciplines. One of the objectives in assembling the steering committee was to have representation covering each of the major lunar data sets, including the lunar samples. An initial face-to-face meeting of the steering committee was held at the 29th Lunar and Planetary Science Conference. It is intended that a strong steering committee will remain in place throughout the duration of the initiative, and that it will form a core of team leaders for the capstone publication. It is not feasible to include all of the experts within each topical area on such a steering committee, but all members of the community are certainly invited to participate in the initiative and others will be encouraged and expected to take on specific leadership roles as the initiative progresses.

At the present time, Ryder and Jolliff continue to co-chair the Initiative, and Neal and Lucey have taken on additional responsibilities related to costing the capstone publication and assisting with organization of workshops. With Papike (currently CAPTEM chair) these five will be largely responsible for coordinating, encouraging, and facilitating Initiative activities, including the tasks listed in this Proposal. We list as collaborators to this proposal the other members of the scientific organizing committee for the September 1999 workshop; these individuals have volunteered their time and have taken on significant leadership roles related to accomplishing goals of the Initiative, and will continue to do so in the immediate future. The list of collaborators may vary from year to year as others also assume leadership roles related to subsequent workshops and within the concept of team organization. The success of the initiative, however, now rests in large measure with the participation and support of the lunar science community. For the activities planned thus far (workshops, publications), organizing committees will be selected from among the steering committee members, or as recommended by members of the steering committee.

Funding through this Proposal will be managed by the LPI, with Ryder as the Principal Investigator.

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### **Facilities: The LPI**

The Lunar and Planetary Institute will manage funding for this proposal, for Workshops and for Publication charges for a capstone publication. The Lunar and Planetary Institute, operating under NASA funding, has dedicated personnel with great experience in the organization of both workshops (at its home location as well as off-site locations) and in publication issues.

## Appendix 1

### Workshop On New Views Of The Moon: Integrated Remotely Sensed, Geophysical, And Sample Datasets List of Presentations

September 18–20, 1998 Houston, Texas

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- Allen C. C., Weitz C. M., and McKay D. S. (1998) [Prospecting for Lunar Oxygen with Gamma-Ray Spectrometry and Multispectral Imaging](#). p. 19–20.
- Basu A. and Riegsecker S. E. (1998) [Reliability of Calculating Average Soil Composition of Apollo Landing Sites](#). p. 20–21.
- Billings T. L. and Godshalk E. (1998) [Probing Lunar Lava tube Caves by Radar Illumination](#). p. 21–22.
- Campbell B. A., Campbell D. B., Thompson T. W., and Hawke B. R. (1998) [Integrating Radar, Multispectral, and Landing Site Data for Analysis of the Lunar Surface](#). p. 23–24.
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- Cooper B. L., Hoffman J. H., Allen C. C., McKay D. S., (1998) [Exploration of the Moon with Remote Sensing, Ground-penetrating Radar, and the Regolith Evolved Gas Analyzer \(REGA\)](#). p. 25–26.
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- Gaddis L. R., Rosanova C., Hawke B. R., Coombs C., Robinson M., Sable J. (1998) [Integrated Multispectral and Geophysical Datasets: A Global View of Lunar Pyroclastic Deposits](#). p. 29–31.
- Gillis J. J. and Spudis P. D. (1998) [Differences Observed in Iron Content Between Crater Ejecta and Surrounding Mare Basalt Surfaces: Implications for Sample Remote Sensing Integration](#). p. 31–32.
- Grier J. A., McEwen A., and Strom R. (1998) [Use of a Geographic Information System Database of Bright Lunar Craters in Determining Crater Chronologies](#). p. 33.
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- Hapke B. W., (1998) [The Vapor Deposition Model of Space Weathering: A Strawman Paradigm for the Moon](#). p. 34–35.
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- Head J. W. III (1998) [Lunar Mare Basalt Volcanism: Stratigraphy, Flux, and Implications for Petrogenetic Evolution](#). p. 38–40.
- Hiesinger H. (1998) [The Lunar Source Disk: Old Lunar Datasets on a New CD-ROM](#). p. 40–41.
- Hiesinger H., Jaumann R., Neukum G., Head J. W. III (1998) [Investigation of Lunar Mare Basalts: An Integrated Approach](#). p. 41–42.
- Jolliff B. L. and Haskin L. A. (1998) [Integrated Studies of Impact-Basin Ejecta as Probes of the Lunar Crust: Imbrium and Serenitatis](#). p. 42–44.
- Keller L. P.\* Wentworth S. J. McKay D. S. (1998) [Surface-Correlated Nanophase Iron Metal in Lunar Soils: Petrography and Space Weathering Effects](#). p. 44–45.
- Korotev R. L. (1998) [Compositional Variation in Lunar Regolith Samples: Lateral](#). p. 45–46.
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## Appendix 2

### LPSC 30 (1999) Special Sessions related to the Lunar Initiative List of Presentations (oral and poster)

- Blewett D. T., Taylor G. J., Lucey P. G., Hawke B. R., and Gillis J. J., *High-Resolution, Quantitative Remote Sensing of South Pole-Aitken Basin*, #1438.
- Eliason E. M., McEwen A. S., Robinson M. S., Lee E. M., Becker T., Gaddis L., Weller L. A., Isbell C. E., Shinaman J. R., Duxbury T., and Malaret E., *Digital Processing for a Global Multispectral Map of the Moon from the Clementine UVVIS Imaging Instrument*, #1933.
- Elphic R. C., Maurice S., Lawrence D. J., Feldman W. C., Barraclough B. L., Binder A. B., and Lucey P. G., *Lunar Prospector Measurements of the Distribution of Incompatible Elements Gadolinium, Samarium, and Thorium*, #1109.
- Feldman W. C., Lawrence D. J., Maurice S., Elphic R. C., Barraclough B. L., Binder A. B., and Lucey P. G., *Classification of Lunar Terranes Using Neutron and Thorium Gamma-Ray Data*, #2056.
- Freed A. M., Melosh H. J., and Solomon S. C., *Tectonics of Mascon Loading: Resolution of the Strike-Slip Fault Paradox*, #1691.
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### Appendix 3

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